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EXPERIMENTS ON EXTINCTION OF FIRES BY AIRBLAST: FLAME DISPLACEM--ETC(U)

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# EXPERIMENTS ON EXTINCTION OF FIRES BY AIRBLAST

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**Flame Displacement as an Extinction Mechanism**

January 1980

Annual Report

By: Stanley B. Martin

Prepared for:

FEDERAL EMERGENCY MANAGEMENT AGENCY
Office of Mitigation and Research
Washington, D.C. 20472

Attn: David W. Bensen, COTR

Contract No. DCPA01-79-C-0245
FEMA Work Unit No. 2564A

SRI Project PYU 8421







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Current uncertainties regarding interactions of blast waves on fires preclude reliable estimates of the outcome of a nuclear attack on the United States. This study focuses on the threshold air-blast condition for extinguishing fires initiated by thermal radiation. Flame blowout tests with simulated nuclear air-blast waves were conducted in the SRI-developed shock-tube facility on class-B fires both in a flat plate geometry and stabilized behind barriers. The results support the concept of flame displacement as a mechanism of extinguishment. Data on class A fuels in practical configurations

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# SUMMARY


## Problem and Objective

The combined blast and fire effects of nuclear explosions in urban areas have been recognized and documented as operationally significant and important to strategic planning. These effects include (1) the dynamic influences of the air shock passing over ignited materials (i.e., fire enhancement or extinguishment) and (2) perturbations in fire growth and spread caused by the blast-induced disarray in the target.

Current uncertainties regarding the various interactions of blast waves and their effects on fires (and on the potential for fire spread to increase damage, destruction, and life loss) are major obstacles to defense planning and countermeasure preparation; they can even affect National Security decision-making at the highest levels. Concisely stated, these uncertainties substantially preclude any reliable quantitative estimates of the outcome of nuclear attack on the United States and of our capacity to survive and recover from such an attack.

Several of the critical uncertainties are:

(1) Threshold air-blast conditions for the extinction of fires initiated by thermal radiation.

(2) Process of rekindle in fuels perturbed by blast.

(3) Effects of structural damage on the processes of fire growth and spread.

(4) Descriptions of debris fields in sufficient detail to permit calculation of fire-spread rates and burning rates.

The Work Unit reported here is an experimental investigation of the first area of uncertainty listed above. The overall objective of this project is to determine and evaluate the physical variables that govern extinction of sustained burning, in representative urban fuels, caused by exposure to simulations of airblast from nuclear explosions. This is a report of

the first year's results, summarizing a somewhat preliminary effort limited to flat-plate geometry in edge-on attitude to the incident shock.

## Experimental Method

Flame blowout tests were run in the SRI-developed shocktube facility, which is specifically designed for investigating the interactions of blast with fire by direct observation of the phenomena and dependence of these phenomena on the basic characteristics of nuclear air-blast waves. The facility provides repeatability of test conditions and convenience of operation, and allows many tests to be conducted in a relatively short experimental program at reasonable cost. Systematic investigation is possible through independent variability of air-blast characteristics over the practical range of values for civil defense concerns.

This facility has been used during 1979 for experiments in air-blast blowout, mostly of Class-B (i.e., hexane-fueled) fires. Only a modest experimental effort was possible because modification of the facility to accommodate these experiments absorbed a substantial part of the available funds.

## Findings

The limited data resulting from this study, as yet unstructured by a theoretical model, allow us to offer only tentative conclusions. Within limitations of the test facility and conditions imposed, the following conclusions seem justified for the flat-plate geometry, zero angle of attack attitude, and for volatile class-B fuels stabilized mechanically by inert substrates:

(1) Flame displacement is a mechanism of extinguishment.

(2) Extinction threshold conditions scale with fuel bed length; more specifically, for 70 to 300 ms pressure-pulse durations, the critical bed length is approximately proportional to peak overpressure (in the range of 1 to 5 or more psi) and appears proportional to particle displacement during the positive phase. The critical length is, however, only about 1/6 of the particle displacement for the waveform used.

(3) Results do not seem to depend upon the texture of the substrate.

(4) The effect of a barrier is pronounced and apparently very sensitive to location. Even a small perturbation introduced into the flow immediately in front of the fire may allow it to survive air-blast conditions that would otherwise readily blow the fire out. However, this "stabilizing wake" does not persist to appreciable downstream distances (less than, say, ten barrier heights).

The single datum on a class-A fuel is totally inadequate to permit comparisons with class-B fuels. However, the displacement mechanism seems to apply also to extinction of flames over class-A fuels in flat-plate configurations oriented edge-on to the incident shock.

## Recommendations for Further Work

This experimental work should be continued. In particular, data on class-A fuels in practical configurations are needed. Acquisition of such data may be delayed, however, until a suitable thermal radiation source can be provided for use with the shocktube. We urgently recommend the development of such a source.

In the meantime, the imbedded heater technique that was developed in a preliminary way in the work reported here should be improved and used to ignite class-A fuels. Also, more work should be done on effects of barriers and other flow perturbing factors to better define the stabilizing influences of complex targets.

At the same time, a separate theoretical development should proceed, with continual interaction between theoretician and experimenter. An effort should be made to minimize the work required to test the seemingly endless variety of variables and their combinations that pertain to practical situations of concern. This might be done by deriving data-correlating parameters from an engineering (i.e., similarity-principle) analysis based on the heat and mass transport process coupled to the relevant processes of chemical change (i.e., pyrolysis and combustion). However, this development should be supported by a more fundamental experimental study

of the physics of interaction of air blast with fire processes in somewhat more idealized fuel bodies than we are using in the present study. Such fundamental studies can, nevertheless, be conducted in the same shock-tube facility.

## ADMINISTRATIVE INFORMATION

This is an annual report of work accomplished under Contract No. DCPA01-79-C-0245; the Statement of Work for this contract reads:

A. General - The Contractor shall furnish the necessary facilities, personnel, and such other services as may be required to evaluate the resistance to shock-wave blowout of established flaming combustion in composite fuel arrays of representative, practical composition.

B. Specific Work and Services - The work undertaken shall include but not be limited to the following:

(1) The influence of fuel bed configuration, orientation, and surface texture on shock-wave blowout shall be investigated using the SRI-developed Blast/Fire shocktube.

(2) Scale effects, such as the minimum length necessary to prevent extinction of flame by shearless displacement, will be investigated, and effects of non-free-field shock interactions, such as those experienced by fuels inside enclosures, by including in the test section nonfailing baffles and fixed apertures to represent perturbations due to walls and windows.

The scope of this effort was further delineated in a contract initiation conference between the COTR and project principal investigators. A detailed approach was subsequently documented in a formal Work Plan.*

With the publication and distribution of this report, all contractual requirements to date are satisfied.

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*Stanley B. Martin, "Blast/Fire Interactions: Research Related to Experimental Extinguishment of Fire by Blast," Work Plan (Work Unit 2564A), SRI Project PYU 8421, SRI International, Menlo Park, CA 94025 (July 1979).

## INTRODUCTION

Fire has long been the single most destructive agent in time of war, and it has figured significantly in many natural disasters. In warfare, fire's preeminent role as a destroyer of man and his works appears undiminished by the replacement of conventional weapons with nuclear weapons. Rather, the intense pulse of thermal radiation emitted by the fireball of a nuclear explosion can light more fires than the heaviest fire-bomb raids of World War II. One large nuclear weapon might cover much of a thousand-square-mile area with fires.

Fire from a nuclear-weapon attack threatens not only the population but also national viability and economic recovery. It can destroy the structural part of the urban environment that survives blast effects, as well as the heavy equipment and other industrial machinery essential to productivity, resupply, and reconstruction.

There are some limiting factors, however, to potential fire damage. Sustained ignition by thermal radiation occurs most readily in the thinner materials exposed to it, and major fires develop only after some time has passed, during which some of the light-fuel fires are particularly susceptible to extinguishment. Within a few seconds to a minute after the thermal flash from a nuclear burst, the blast arrives and may blow out many of these young fires. If the blast wave dramatically reduces the number of persistent fires, this could reduce the problem of firefighting in these areas. However, none of the interactive effects of air blast and fire is sufficiently well established to allow one to conclude confidently whether the situation will be improved or worsened.

For a considerable time, such interactive effects of blast and fire have been recognized, but only a limited research effort has been directed toward understanding and quantitatively evaluating them. These effects include the dynamic influences (enhancement as well as extinguishment)

of the passage of the air shock over ignited materials and the perturbations in fire growth and spread caused by the residual disarray produced in target elements by blast effects. This research has, to date, provided some insight, but the remaining contradictions can be resolved only through additional experimental study, complemented by the development of a rational methodology for combined-effects damage assessment.

Of the several critical uncertainties, perhaps the one that overshadows all others is the extinction (or suppression) of fire by air blast since it raises such questions as: how many (if any) fires survive the blast, in what conditions, and in what locations? In short, the combinations of conditions that either suppress primary fire starts--reducing them for a time to a smoldering state--or extinguish them outright cannot be predicted. The research work reported here is an initial attempt to determine the basic physical mechanisms of interaction between burning objects and air blasts in the practical context of nuclear-weapons effects on urban and urban-like situations.

## BACKGROUND

### Previous Experimental Studies

The earliest published study of extinction of flames by nuclear air blast simulation was the experimental investigation in the early 1950s by Tramontini and Dahl and their colleagues at UCLA.[1-3] They ignited typical forest fuels (and crumpled newspaper) with 1- to 3-second exposures to thermal radiation from hot silicon carbide plates. After a controlled delay, the burning fuel beds were blasted with air from a compressed air plenum. Maximum flow velocity and duration of flow were independently varied; however, independent control of peak overpressures was not attempted, since it was assumed at the outset that passage of the shock front would be relatively unimportant in extinguishing fires compared to the "cooling effect" of the flow behind the shock. Moreover, they made no provisions for maintaining overpressure (that is, for delaying rarefaction) through the period of plenum blowdown, and, while flow continued for periods as long as 3 seconds, overpressures fell to zero within a few milliseconds.

Extinction thresholds were expressed in terms of air velocity following the shock, but actually neither velocity nor overpressure was measured in the location of the specimen; rather, these were inferred from measurements at the plenum exit prior to expansion to the full cross section of the tube. Tank pressure decayed monotonically with time at a rate determined by orifice size. Limited measurements of orifice velocities showed a nearly linear decay over the duration of flow, in quantitative agreement with theory. The authors of Ref. 2 concluded that test-section velocities behaved the same and were therefore reliably computed from orifice size and initial conditions (i.e., tank temperature and pressure). The test parameter used to characterize the "strength" of the blast was the calculated initial (or peak) velocity, corresponding to the flow

following immediately behind the shock. Threshold values were those estimated to extinguish flames in 50% of the trials; smoldering combustion was not extinguished. No significant differences were found between the extinction thresholds for horizontal and near-vertical arrays of pine needles, and there were no regularities in effect of orientation shown by the other materials as a group.

The threshold values for flame extinction, $V_o^*$, were found to depend on flow duration, $\theta_F$; the delay between ignition and blast, $\theta_B$; the bulk density of the fuel, D; and on the moisture content of the fuel, M. For Ponderosa pine, the material most tested, Tramontini and Dahl[2] fit their data with the following empirical equation:

$$V_o^* \text{ (in ft/sec)} = (7.93\ \theta_B - 16.8\ D + 157)M^{-0.125}\ \theta_F^{-0.413}$$

This equation is strictly applicable only to the ranges of their test variables, which were

$$0.27 \text{ sec} \geq \theta_F \geq 2.76 \text{ sec}$$

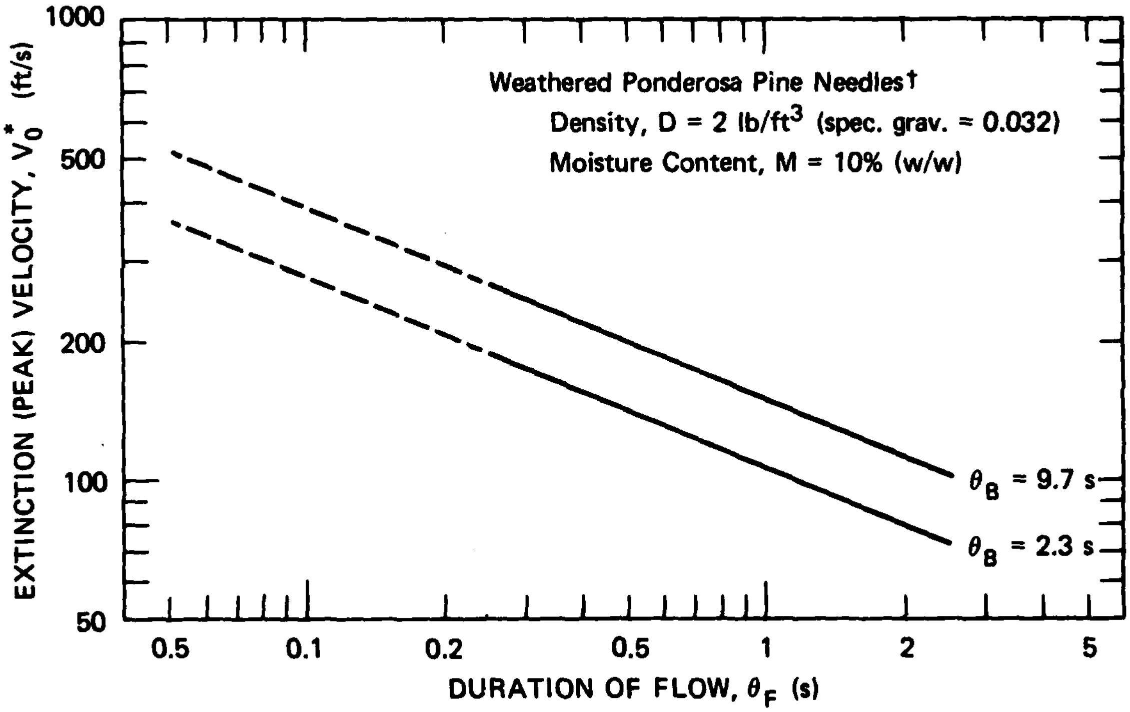
$$2.3 \text{ sec} \leq \theta_B \leq 9.7 \text{ sec}$$

$$1.5 \text{ lb/ft}^3 \leq D \leq 3.2 \text{ lb/ft}^3$$

$$1.5\% \leq M \leq 20\%$$

Figure 1 illustrates this empirical conclusion over the applicable ranges of $\theta_F$ and $\theta_B$ for a target having a bulk density of 2 lb/ft$^3$ (characteristic of furniture cushions as well as ponderosa pine needle beds) and a 10% moisture content. The dashed lines are calculated extrapolations of the empirical equation to smaller values of $\theta_F$.

After the UCLA studies ended, no further experimental attention was given to the problem of extinction of fires by air blast until the late 1960s. At that time the URS shock tunnel facility at Ft. Cronkite, California, was completed, and appropriately furnished rooms could be subjected to air blast simulation. The part of the facility initially used for these experiments[4] was limited to short positive-phase durations, typically 80 ms--that is, only 2 to 3% of the duration of a moderate overpressure,




†Computed from empirical equation of Tramantini and Dahl (Ref. 2)

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FIGURE 1 RESULTS OF EARLIER UCLA STUDY

free-field blast wave from a megaton-yield air burst. Despite such limitation, however, the simulation can represent many strategic situations. For example, as the tests were conducted in the URS facility, with shock incident on the (simulated) exterior wall of the room and constrained from rapid decompression by the walls of the tunnel, the resulting reflected pressure maintained a reservoir of compressed, adiabatically heated air to support flow into the room for long periods relative to filling times. Thus, in the set of experiments conducted by Goodale,[5] where the walls of the room were designed not to collapse under the imposed load, the reservoir pressure persisted until the room was effectively filled as it would have been if subjected to a much longer air blast wave.

Therefore, in cases where the confining walls do not fail, the differences in positive-phase durations, represented by the URS shock tunnel simulation and the much longer durations of megaton air bursts, may not be of practical importance. In addition, the early time flow fields, which may be the main determinants of whether or not flames are extinguished, are determined by the <u>initial</u>* pressure differential (outside to inside) that drives the flow and are quite insensitive to the room orientation and geometry.

Using furnished rooms as full-scale simulations in the URS shock tunnel, Goodale found that:

- A threshold value of incident blast overpressure in the range of 1 to 2.5 psi is required to extinguish all flames in the test rooms.

- This threshold is not markedly affected by the size of the windows through which the blast propagates; from this observation the author concluded that extinguishment of flame over the surface of interior kindling fuels is not determined solely by particle velocity of the flow near the burning object nor by its duration.

- Kindlings that support smoldering combustion will continue to smolder following extinction of the flame. (Smoldering debris commonly resumed active flaming after delays ranging from minutes to hours.)

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*Therefore, these flow fields are independent of the postive-phase duration of the free-field air blast that loads the exterior of the structure if walls remain intact.

- High-speed motion pictures revealed at least one instance of flames being swept from the burning surface, apparently by shearless displacement that accompanied shock diffraction, suggesting the importance of a sudden (or discontinuous) pressure rise.

The second finding above (and the conclusion associated with it) suggests that either pressure or pressure change is important to the mechanism of shock extinction.

Two subsequent studies conducted by Goodale[6,7] in the URS tunnel are noteworthy. In 1971, Goodale[6] explored the effects of higher overpressures (to a maximum of 9 psi) on the residual smolder that had consistently been observed after the blowout of flames at 2.5 psi. The higher overpressures did not produce a smolder-extinction counterpart to the blowout of flames; no trend was evident between 5 and 9 psi. Cushions filled with polyurethane foam and kapok failed to smolder after flame blowout at all overpressures. Goodale concluded that cotton batting may be especially susceptible to smoldering and, therefore, items containing this substance may represent a special hazard that could be eliminated by excluding this material.

In a separate study,[7] Goodale tried to quantify the hazard due to burning curtain fragments transported through windows by the flow following shocks of lower overpressure. (All experiments were conducted at 1 psi to avoid blowout.) He concluded that the transport of burning fragments by blast can be extremely hazardous, but that this mechanism depends critically on the time the blast wave arrives relative to the stage of burning of the curtains or drapes, which in turn is a function of the weight of the fabric used in the window hangings. He recommended further investigation of these dependencies because of the great incendiary potential represented by this synergistic interaction between thermal ignition and blast, even at relatively large distances from ground zero.

In a later study,[8] Wilton et al. used the URS "Long Duration Flow Facility (LDFF)" and found that the placement of the burning item in the room, relative to entries and exits, and the fuel type were critical variables for extinguishment. Both cellulosic and synthetic materials were investigated. Some items were confined and others were unconfined; all

were flaming at the time of simulated blast arrival. The experimental conditions included flows equivalent to those that would result from reflected pressures, external to the chamber entrance, of 2 to 4 psi.* Extinguishment occurred only when samples were located in regions of high flow velocities (near entrances, exits, and in some geometries, near the center of the room); permanent extinction occurred only in lightweight fuels. In heavier fuels, complete extinguishment never occurred; rather, flaming subsided to a smolder, rekindling to flame within a few minutes.

During Operation MIXED COMPANY, Wiersma and Martin[9] participated in a 500-ton TNT explosion test to seek the scaling relationships for the interactions governing the air blast extinction process. Shearless displacement of the flames did not occur, and none of the fires was extinguished, even at the 5-psi station. The horizontal fuel beds of liquid hydrocarbon, mechanically stabilized with a gravel "wick," were essentially flush with the ground, and the nonideal shock behavior near the ground might account for the unexpected and seemingly contradictory behavior. After the test, the shock was reported[10] to be appreciably degraded near the ground surface. Thus, the fuel beds probably experienced a gradual pressure rise and potential flow accompanied by an already established turbulent boundary behind the shock. They also might have been subjected to a substantially reduced overpressure. Moreover, since a liquid hydrocarbon was used instead of the usual solid fuels of urban enclosures, the result could be due in part to the relatively high vapor pressure and low latent heat of vaporization of the hydrocarbon fuel.

At the 120-ton high-explosive detonation of Misers Bluff, SRI assisted the Ballistics Research Laboratory in an attempt to establish at least one experimental point of high confidence. The test object was a well-anchored cushion of vinyl-covered polyurethane foam, one-half of which had been covered with cotton terrycloth to enhance smolder. The cushion was positioned well above the ground surface and exposed first to a thermal fluence of nearly 20 cal $cm^{-2}$ from an aluminum/oxygen thermal

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*Note, however, that in the LDFF a true pressure discontinuity is not produced and the pressure differentials are mainly dynamic.

source, and then, (2 sec later), to a 7-psi shock.

The radiant-heat source apparently ignited the pillow, as intended, but $AL_2O_3$ powder obscured the entire sequence of events so that the monitoring motion pictures do not show the ignition and extinguishment. Other motion pictures reportedly taken from a more advantageous position are not available. Observation after the explosion indicated that the fire had been initiated in both halves of the cushion by the thermal exposure and then completely extinguished by the subsequent shock wave.

## Theoretical Background

Currently, there are three mechanistically distinct concepts that serve as bases for theoretical analysis of blast extinction and can provide hypotheses for experimental tests. However, their formal development as mathematical models of blast extinguishment is incomplete. Theoretical derivations have been limited primarily to conditions of steady laminar flow. Only one theory deals with the dynamics of shock waves, and even in that case, principles of steady-state boundary layers must be used to obtain numerical evaluation.

For present purposes, we will refer to these three concepts as:

- Shearless displacement
- Critical flame stretch (flame strength)
- Critical quench distance (flame standoff).

Each of these is described briefly below.

Shearless displacement--As a plane shock wave diffracts across a solid object, the pressure discontinuity is supported by fluid flow that, even very close to the surface of the object, is not appreciably affected by viscous shearing stresses; that is, the inertial forces dominate over the frictional forces, the former being many millionfold larger than the latter, even for relatively weak shocks. If a flame has been established over the solid object before the arrival of the shock, it can be swept cleanly away from its original location, leaving relatively cool air (and no fuel vapors) as the fluid medium adjacent to the surface of the solid object. If the dimension of the object along the path of shock propagation

is small, the flames may be swept completely away from the burning surfaces, leaving them unable to continue combustion. However, if the burning surface is large, the flames may not be swept cleanly from the entire area; hence the flames will quickly reestablish themselves following the brief interlude of shock diffraction and inertial flow.

Immediately behind the shock front, as it sweeps over an extended surface, a boundary layer forms in which friction with the surface slows down the fluid near the surface relative to the free stream; this gives rise to a steep gradient in velocity and severe shear stresses. Eventually, but often in a time much shorter than the duration of the positive overpressure phase, the velocity in the boundary layer slows to the point where the flame can remain anchored despite the shear stress. From that time and location, the flame begins spreading inexorably upstream to reestablish itself.

The consequence of this process would be a cause/effect relationship between boundary layer growth and critical length of fuel bed. It would suggest a strong dependence on orientation and sources of turbulence, including barriers and surface irregularity.

Critical flame stretch--In a theory of the extinction of diffusion flames by steady, laminar air flow (classical wind-tunnel conditions), Spalding[11] postulates an upper limit to the combustion rate of any gaseous fuel in air. He designates this limit as "flame strength." He shows that this limiting rate for diffusive burning is of the same order as the combustion rate of the same fuel in a stoichiometric premixed flame. The diffusion flame's location (relative to the source of fuel supply) and its rate of combustion are determined by physical transport processes. These processes, which are necessarily diffusive in the absence of turbulence, control the rate at which the fuel and oxidant molecules encounter one another. Ordinarily, chemical reaction rates are comparatively so rapid that they may be considered to occur instantaneously on contact of the reactants. However, in the velocity gradient of the fluid boundary adjacent to a solid surface, rates of physical mixing may become comparable to reaction rates. Then the flame seeks out a stable location closer to the

solid surface (which is also the source of the gaseous fuel), and the resultant rate of combustion is higher. If the free-stream velocity is further increased, the flame moves still closer to the surface and the reaction rate increases until the critical rate of the chemical reaction is reached. At this point, the flame will "break" and appear to be "blown downstream" to a new stable point, where the velocity gradient permits the reaction to proceed at a rate less than the critical value. If the free stream velocity is then decreased (or if the condition of fluid-solid interaction causes the boundary layer to increase in thickness), the flame will reestablish itself; that is, it propagates against the fluid flow until it more or less resumes its original position.

The phenomenon of breaking of the flame sheet in a steep velocity gradient resembles the stretching of an elastic membrane to its limit of strength. This led Karlovitz[12] to propose the term "flame stretch" and to quantify the break point in terms of the velocity gradient normal to the burning surface. This concept is entirely analogous to Spalding's theory, from which it is derived.

Perhaps the simplest illustration of this concept is a fuel-wetted sphere burning in a uniform velocity stream of air. The point of highest shear stress is the upstream stagnation point. Here, the flame will break when the free-stream velocity is sufficiently increased. The geometry is a convenient one because it lacks the ill-defined leading edge of a plate or any other flat-sided object.

Experiments have been conducted with spherical liquid drops and with spherical wicks of porous solids saturated with liquid fuels.[13-15] The critical free-stream velocity has been found to depend on sphere diameter and to vary with both the latent heat of volatilization of the fuel and the ambient temperature. In particular, the critical velocity, corresponding to a break in the flame at the forward stagnation point, has been found to increase with sphere diameter, to decrease on substitution of liquid fuels requiring more heat to vaporize, and to increase with ambient temperature.

Using kerosene as the fuel, Spalding[13] found a direct proportionality between the critical velocity and sphere diameter. This he offered as

evidence in support of his flame-strength theory of extinction. In contrast, Agoston, Wise, and Rosser,[14] using n-butyl alcohol as the fuel, observed extinction velocity to vary as the square root of drop diameter.

Aside from this unresolved contradiction, Spalding's theory satisfactorily accounts for the available experimental data on extinction by steady flows.

Critical quench distance--Another plausible explanation for the experimental facts described above involves the quenching of flames within a small distance of a solid surface. The theory is not well advanced for diffusion flames, but there is a wealth of empirical information for premixed flames that can be explained theoretically, and it seems likely that some correspondence of principles will apply to diffusion flames.

Fundamentally, when an established flame burns in proximity to a solid surface that acts as a sink for heat and reactive intermediates, these may diffuse to the surface fast enough to lower the temperature and/or concentration of reaction intermediates below the level needed to maintain a stable flame, and local extinction occurs. At atmospheric pressure, these distances are on the order of millimeters. In Spalding's experiments[13] with kerosene-wetted spheres, the distance separating the liquid surface from the visible flame had a minimum value of about 0.036 inch ($\sim$0.9 mm) immediately before extinction, regardless of the drop diameter. Agoston et al.[14] report the same constant separation distance for porous spheres wetted with both ethyl alcohol and n-butyl alcohol. Reporting on the experimental burning of cellulosic solids, Parker[16] estimated the standoff distance for visible flames at about 1 mm.

## Objectives of the Present Research

The general long-term goals of this investigation are to:

(1) Provide practical insight into the importance of blast wave extinguishment of fires caused by nuclear explosions in situations that are relevant to civil preparedness.

(2) Lay the empirical groundwork for generalized extrapolation and predictive modeling of the outcome of interactions between air blast and fire in practical circumstances.

The work reported here is an initial effort. Its purpose was to evaluate the resistance of air blast blowout of established flaming combustion in composite fuel arrays of representative, practical composition. The specific objectives were to:

(1) Investigate, using the SRI-developed blast/fire shocktube, the influences of fuel bed configuration, orientation, and surface texture on flame blowout.

(2) Investigate scale effect (e.g., the minimum fuel bed length necessary to prevent extinction) and non-free-field effects (e.g., those experienced by fuels inside enclosures) by including in the test section nonfailing baffles and fixed apertures to represent perturbations due to walls and windows.

This work is intended to be a complementary effort to theoretical developments (e.g., Work Unit 2563E) and a separate, DNA-funded, experimental study of the basic physics of interactions between air blast and flames on targets of idealized geometry supplied with model fuels. Completion of the SRI-developed blast/fire shocktube facility at USAG Camp Parks was funded by DNA as a necessary preliminary to fundamental experimentation; however, subsequent funds to proceed with the research have not been forthcoming. Moreover, since the theoretical complements have not developed apace, this project has necessarily proceeded without the help of output from the other elements of the planned program.

# EXPERIMENTAL APPROACH

In all previous experiments, the blast-wave simulations have been inadequate to permit resolution of the many variables involved in most practical situations. The fundamental weakness in experiments conducted to date has been their lack of independent variability of peak overpressure, positive-phase duration, and flow behind the shock front. Such variability would allow systematic study of fire extinguishing mechanisms and the dependence of extinction on pertinent aerodynamic conditions that can vary so widely in an urban target.

The SRI-developed shocktube facility was specifically designed for use in studying blast/fire interactions by allowing the phenomena to be observed directly, providing repeatability of test conditions and convenience of operation, and making systematic investigation possible through independent variability of air blast characteristics over the practical range of values for civil defense concerns.

## The Experimental Facility

The heart of the facility is a 30-inch-diameter, air-driven shocktube specifically designed for experiments in blast-fire interactions. This shocktube produces blast waves that simulate the characteristics of kiloton-to-megaton nuclear explosions in air. Peak overpressures and positive-phase durations are preselected and controlled by the operator. Overpressures are determined by choice of initial pressure in the plenum that drives the shocktube. The duration is controlled by a mechanism for relief of plenum pressure by diverting a portion of the airflow from the shocktube. The facility is designed to provide peak overpressures up to 25 psi and positive-phase durations from about 0.10 to more than 3.5 seconds. A system of orifices at both ends of the shocktube, combined with a receiver tank at the exhaust end, match the outflow of the receiver tank (when it is fully pressurized) to the outflow of the plenum to

prevent the premature rarefaction of the test section. The facility includes a telescoping test section that allows fires to become established, while burning in the open, before being enclosed. The telescoping section is then closed, just as the shock is initiated, with minimal delay to prevent depriving the fire of oxygen. For safe operation, this closure must occur automatically upon command from a remote location. The study reported here was our first opportunity to use the shocktube with fires. Therefore, it was necessary to make provisions for fuel supply, fuel bed support, and for rapid, semiautomatic closure of the test section. Test target design requirements are complicated by the necessity of supporting the ensemble without interfering with either the operation of the telescoping section or with the shockwave as it approaches the target.

### Test Section Modifications

The initial experiments were visualized to be idealizations of the kerosene/gravel fuel beds used at Mixed Company. To minimize perturbations in the air shock and subsequent flow, a thin, flat plate having sharp leading and trailing edges was chosen as the basic form of the fuel bed support. This platform, illustrated in Figure 2, is rigidly supported in a near midstream position by a sharp-edged cantilever attached to the stationary shocktube section just forward of the test section opening. The platform accepts 10-inch-wide fuel beds of variable lengths up to 36 inches along the direction of shock propagation. The fuel is set into a recess on the top surface and is ordinarily flush with the top surface. The telescoping section is closed on remote command, initiating an automatic sequence to start the cameras; after a 1.6-second delay the film automatically accelerates to full speed, and the line charge asterform on the diaphragm is fired to initiate the shock. A borosilicate glass window in the sliding section allows the fuel bed and flames over it to be observed and recorded on film. Measurements were limited to temperature-time and overpressure-time records. The principal form of target response information, besides the postshot observation of whether or not extinguishment had occurred, was provided by high-speed color

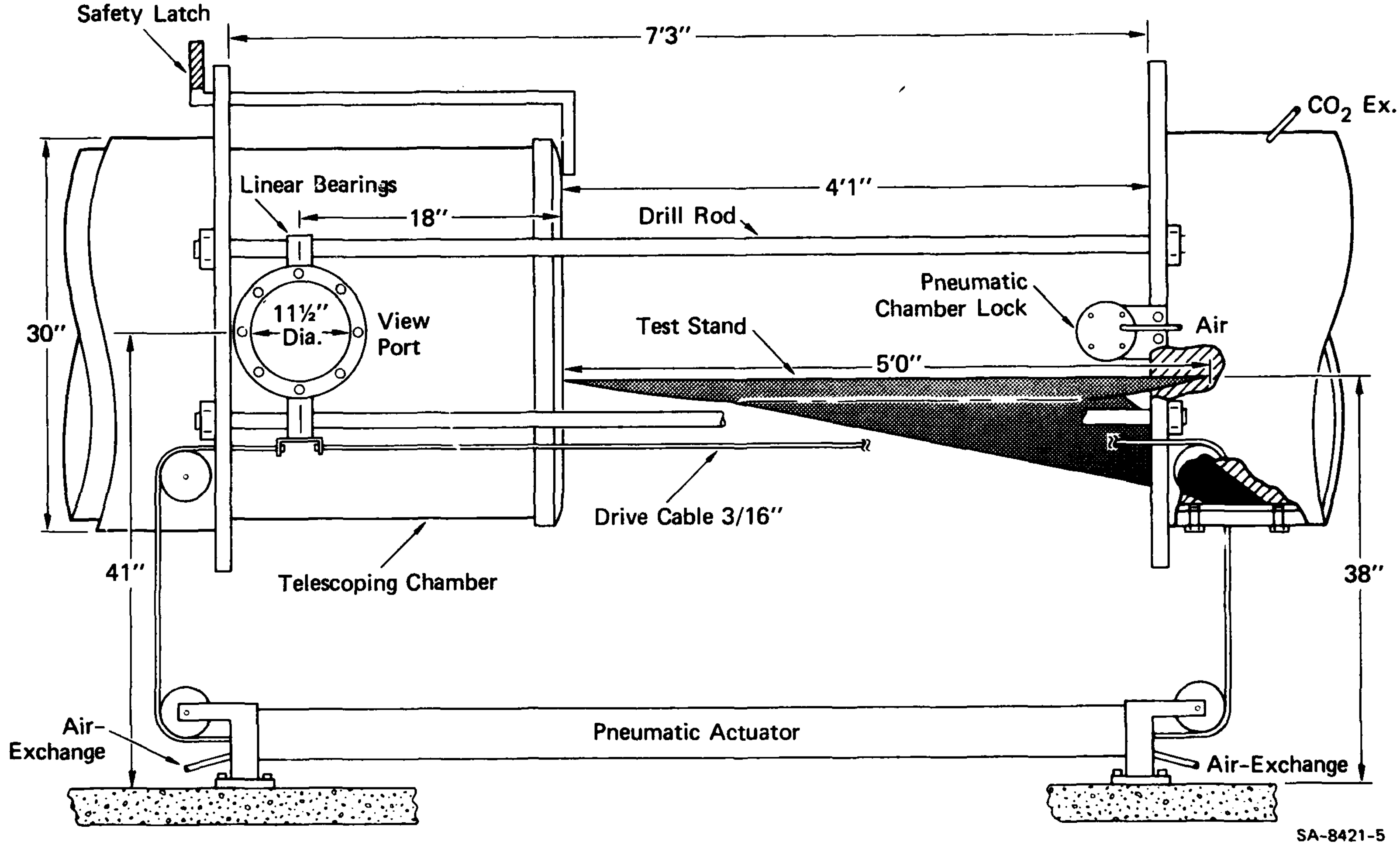


FIGURE 2 SHOCKTUBE TEST SECTION

photography (approximately 2000 frame-per-second framing rate) of the flames during shock diffraction and the period of subsequent hydrodynamic motion.

## Investigation of Flame Displacement over Fuel-Soaked Wicks

n-Hexane was chosen as a class-B-fuel substitute for the kerosene used at Mixed Company. This change was felt to be desirable mainly because the use of a single substance of well-defined properties avoids possible ambiguities of less well-defined mixtures whose properties can change with time, but also because hexane is somewhat cleaner burning (less sooty) than kerosene.

Initially, the substrate was made up of small rocks (of approximately ½-inch diameter) held together with a cementitious adhesive (Sauereisen). Subsequently, two other substrates, with different porosities and surface textures were used: firebrick slabs, joined at their edges with Sauereisen cement, and a single piece of Kaowool M board. Only the kaowool could be used repeatedly without some degradation due to cracking, erosion, and/or loss of material during tests. However, all the substrates held up long enough to allow us to compare their influence on the flame displacement process. In all cases, hexane was supplied from an external reservoir so that the wick would remain fuel-soaked without overflow or drying out during the test.

The first set of class-B fuel tests was run with the longest available positive-phase duration. However, consistent extinction of flames occurred at all overpressures down to about 1 psi (where the pressure spike from the line-charge explosive, used to cut the diaphragm, appreciably perturbs the air-driven pressure pulse). Therefore, we decided to operate in the mode that provides the shortest available positive phases (i.e., blanking off the tank at the orifice flange and using only the 33.5-ft section of tube between the diaphragm and the tank as the pressure plenum). For the remainder of the experimental work reported here, we continued to operate in this short-duration mode.

## Flame Displacement from Class-A Fuels

Our choice of class-A fuel was governed mainly by a desire to use a flat slab of a reasonably homogeneous material. The principal problem was to achieve uniform, sustained ignition over the large specimen area (10 in. x 36 in.) so that the fire could become appropriately established, and still have enough fuel left by shock arrival to continue to support combustion if blast-wave extinction did not occur. After trying several candidates, we settled on ¼-in.-thick hardwood plywood. However, without external heat reinforcement, this material is incapable of sustaining a fire when ignited on one surface only; hence, we preheated the plywood to a "near-critically-hot" condition before igniting it. This was accomplished with electrical heating units under the length of the plywood sheet. Just prior to closing the test section and initiating the air blast, the electrical heaters were shut off and the plywood was ignited by slowly passing a 3-ft-long propane pilot burner over the width of the plywood. Unfortunately, before we could achieve satisfactory operation of this technique, we were forced to discontinue the experiments because of fund limitations.

## Boundary-Layer Perturbations

In an effort to assess the effects of induced turbulence and shear on the displacement mechanism, we ran two of the class-B tests (Tests 5 and 6) with a low barrier erected in front of the upstream edge of the fuel bed. In most other respects, both these tests were intended to replicate a previous test (Test 4) without barrier in which the flame was swept cleanly away in less than 10 ms following shock passage. (Test 4: n-hexane stabilized with rock substrate, 10 in. x 36 in. bed, 45-sec preburn; air-blast wave of classical form, nominal 8-psi peak overpressure, and 3-sec positive phase.) Two different situations were explored:

(1) In Test 5, a 1-in.-high, thin-walled barrier was located ahead of the forward edge of the fuel bed, and thus was interposed in the path of the advancing shock, as it diffracted over the top of the target platform.

(2) In Test 6, a 1.75-in.-high barrier was located at the forward edge of the fuel bed, whose length was reduced to 24 inches.

The pressure pulse recorded at the test section during Test 5 was very similar to Test 4. For reasons that remain obscure to us at this time, Test 6 had a basically different pressure pulse; the waveform was distinctly nonclassical--with a major peak in pressure significantly delayed behind the initial shock. The pressure pulses for these tests are shown in Figures 3, 4, and 5.

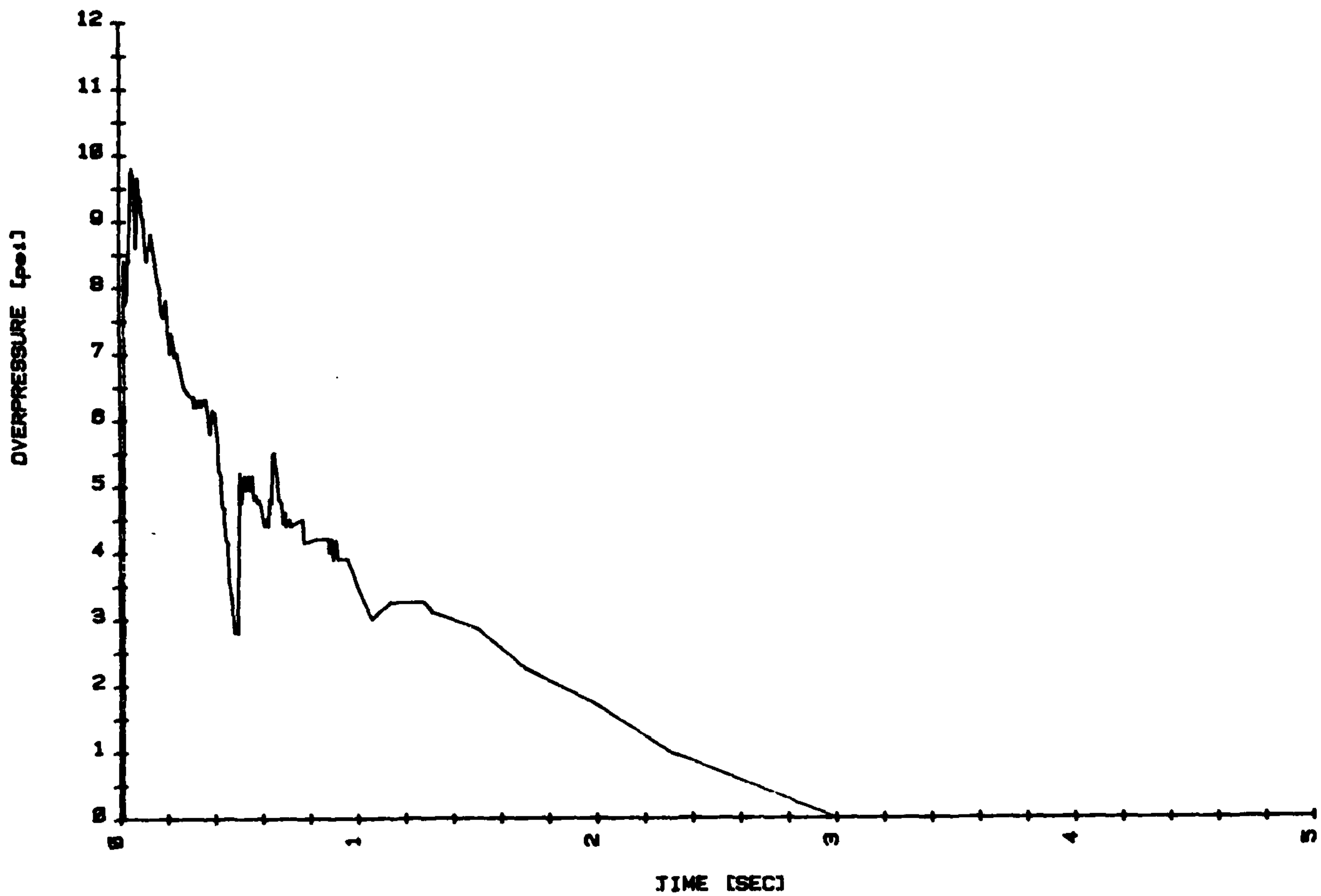


FIGURE 3  PRESSURE-TIME PULSE, TEST 4

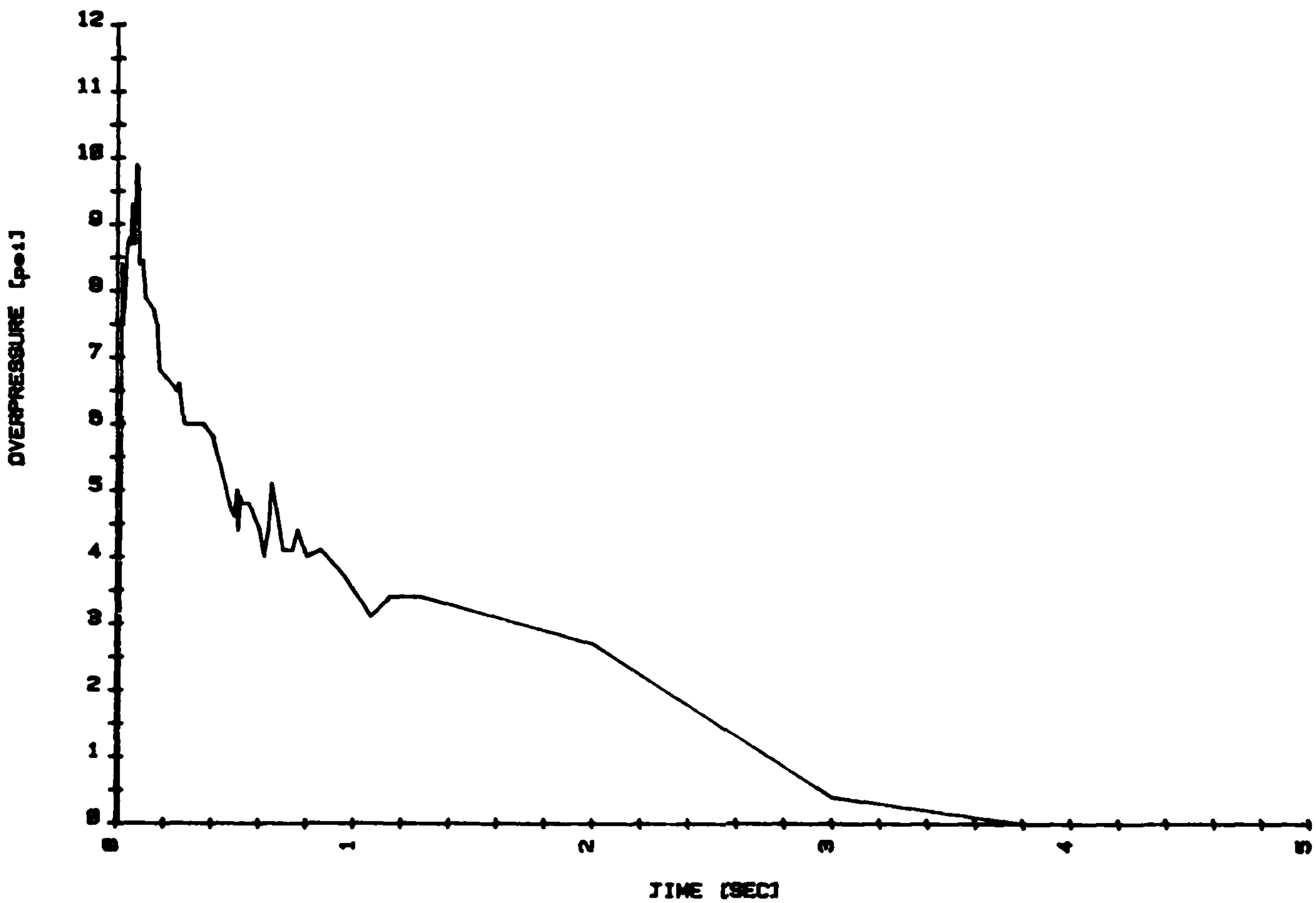


FIGURE 4 PRESSURE-TIME PULSE, TEST 5

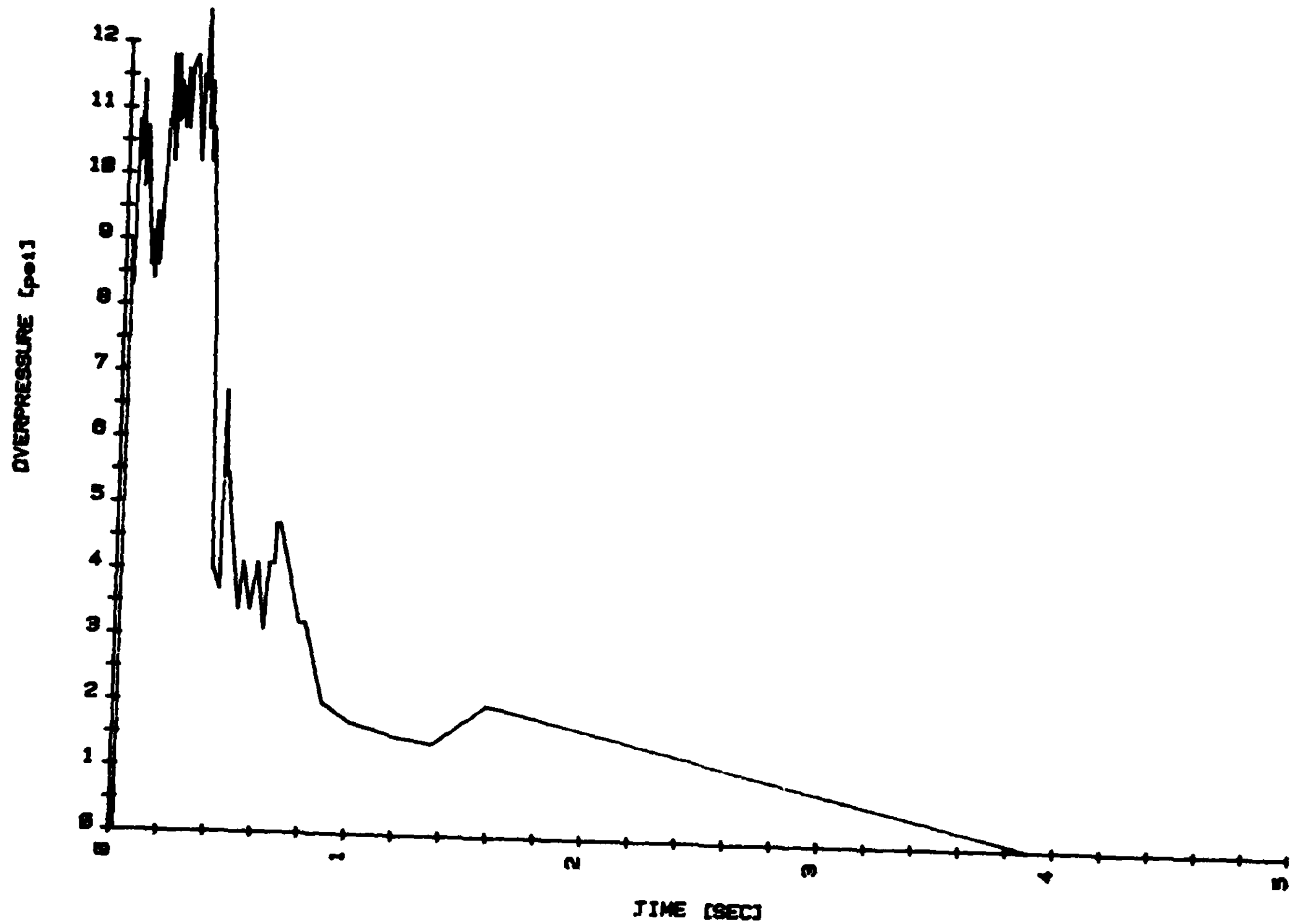


FIGURE 5, PRESSURE-TIME PULSE, TEST 6

## RESULTS

We conducted a total of 28 blast/fire interaction tests, and all but one involved n-hexane-fueled fires. Of the three substrates used to stabilize the liquid fuel, ½-in. rock was used in Tests 1 through 8, firebrick was used in Tests 9 through 17,* and a Kaowool M-board substrate was used in Tests 19 through 28. Only one test (No. 29) was run on a class-A fuel. There were a few misfires in the class-B fuel series. Table 1 summarizes the results.

The first seven tests, which included the two with barriers, were run with the longest available positive-phase durations. All failed to provide a single instance of flame survival; the remaining tests were run with the shortest positive-phase available. By varying both bed length and pressure, we were able to define with considerable exactness the locus of those pressure/length-of-fuel-bed points that describe the threshold of extinction of n-hexane-fueled flames in the short-duration mode, for fixed-bed width and ambience. This result is illustrated in Figure 6. These results seem quite insensitive to substrate material and texture.

The single class-A fuel test was run under conditions that would have failed to extinguish flames over a hexane bed (∿ 3.5 psi peak overpressure and 3-ft bed length in the short-duration mode). The flames were extinguished, but the result is inconclusive because of difficulties experienced in igniting the plywood surface and because not all of the surface was flaming at the time of blast interaction. Nevertheless, the result supports the pre-Mixed Company contention that class-A fires can be extinguished at relatively low overpressures.

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*Test 18 was run without fire to assess the ultimate bursting pressure of the 10-mil aluminum diaphragm material.

Table 1

SUMMARY OF HEXANE TEST RESULTS

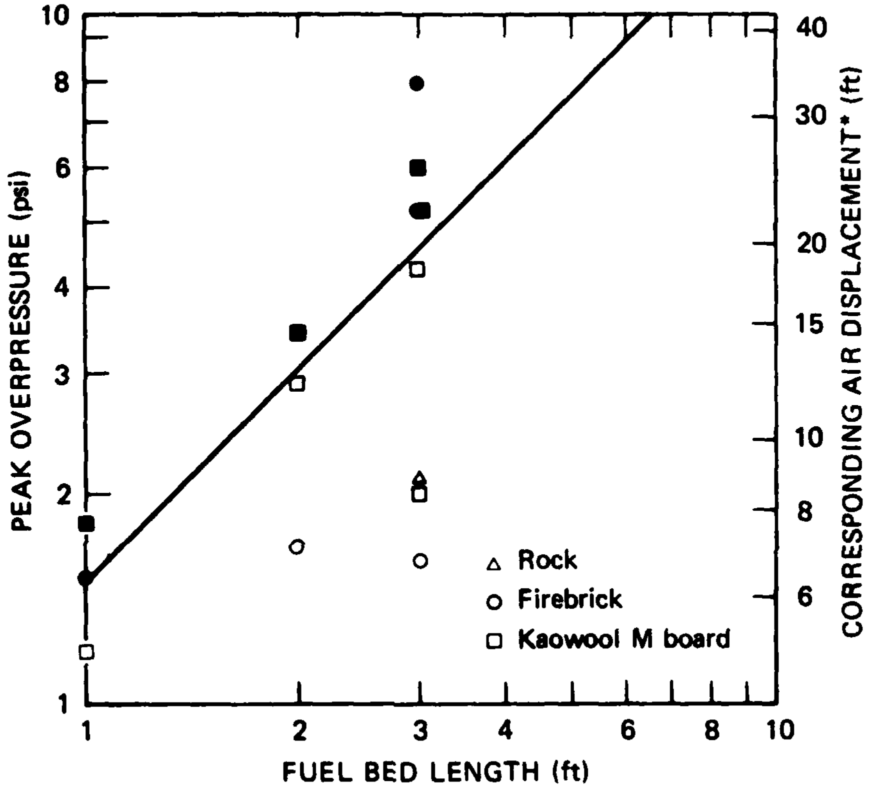
| Test No. | Substrate | Fuel Bed Length (inches) | Est. Peak Over-Pressure (psi) | Positive Phase Duration (sec) | Computed* Air Displacement (ft) | Observation |
|---|---|---|---|---|---|---|
| 3 | rock | 24 | 9 | 3.5 | | fire out |
| 4 | rock | 36 | 8 | 3.0 | 440.0 | fire out |
| 5† | rock | 36 | 8 | 3.8 | 520.0 | fire out |
| 6† | rock | 24 | ∿ 11(nc) | 3.8 | | fire out, but see text |
| 7 | rock | 36 | 1.3 | 0.65 | 35.0 | fire out |
| 8 | rock | 36 | ∿ 2 | 0.35 | 8.2 | fire sustained |
| 10 | firebrick | 36 | 1.4 | 0.3 | | fire sustained |
| 14 | firebrick | 36 | ∿ 8 | 0.2 | 33.0 | fire out |
| 15 | firebrick | 12 | 1.5 | 0.07 | 5.2 | fire out |
| 16 | firebrick | 24 | 1.7 | 0.15 | 8.0 | fire sustained |
| 17 | firebrick | 36 | 5.2 | 0.25 | 23.0 | fire out |
| 19 | kaowool M board | 36 | 2.0 | 0.175 | | fire sustained |
| 20 | kaowool M board | 36 | 4.3 | 0.28 | | fire sustained |
| 21 | kaowool M board | 36 | 5.9 | 0.275 | | fire out |
| 22 | kaowool M board | 36 | 5.2 | 0.31 | | fire out |
| 23 | kaowool M board | 24 | 2.9 | 0.29 | | fire sustained |
| 24 | kaowool M board | 24 | 3.6 | 0.135 | | fire out |
| 25 | kaowool M board | 12 | 1.8 | 0.07 | | fire out |
| 26 | kaowool M board | 12 | 1.2 | 0.07 | | fire sustained |
| 27 | kaowool M board | 12 | NA | NA | | fire sustained |
| 28 | kaowool M board | 12 | NA | NA | | fire sustained |

*Computed as $50 \cdot \int_0^{t_+} p(t)dt$; where $p(t)$ is the pressure-time record at the test section (in psi) and $t_+$ is duration of the positive phase of that record.

†Test with barrier.

nc - Nonclassical waveform

NA - Test run with line charge only, no plenum pressure.




*See Appendix A.

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FIGURE 6 EXTINCTION THRESHOLDS FOR n-HEXANE; SHORTEST POSITIVE-PHASE DURATIONS

Filled symbols indicate tests in which flames were extinguished.

The characteristics of the short-duration pressure pulses show some interesting trends that are not currently understood. For the cases in which we computed air particle displacement distances during the positive phase by the method outlined in Appendix A, we find a reasonably good fit to the linear relationship:

$$d_+/p_o = 4.2 \text{ (ft/psi)}$$

where $d_+$ is the displacement and $p_o$ is the corresponding peak overpressure. This result, showing no dependence of displacement on duration, is unexpected; however, the main surprise is that positive phase duration varies not with overpressure but with fuel bed length. The data in Table 1 show this remarkable effect of fuel bed length on duration and an almost total lack of any systematic effect of pressure on it. In situations having no fire present, as well as the cases involving the smallest fuel bed, the duration is consistently close to 70 ms. Cases involving the 2- and 3-foot beds had appreciably longer durations, some as long as 300 ms; and yet the pressure-time integral from which fluid displacement was estimated scales with peak overpressure, and is independent of duration.

Evidence of Displacement and Other Flame/Flow Interactions

Cursory viewing of the high-speed motion picture records of all tests reported here (with the possible exception of No. 6) leaves no doubt that flame displacement provides a mechanism for extinction in class-A as well as class-B fires. Moreover, this conclusion, because of the dependence of fluid displacement on overpressure, is certainly consistent with the near-linear relationship between extinction-threshold bed length and overpressure (previously shown in Figure 6). If flames are displaced bodily along with the air in the blast wave, then they will be translated a distance that is also proportional to the overpressure.

However, a careful scrutiny of the cine film, frame-by-frame, reveals distortions in flame shape that are not totally consistent with the concept of displacement without shear. There are not only changes in shape (on a scale of time and distance that is inconsistent with fluid motion and boundary layer growth), but also abrupt changes in flame state. To what extent these complexities may be relevant to the practical

applications of this research, we cannot ascertain at this time. They do, however, indicate that the concept of extinction of flame by bodily displacement is mechanistically naive.

A few examples illustrate this point. The high-speed motion pictures--viewed a frame at a time--typically show the following features and general chronology. One frame shows the transmission of the shock front as a blurring of the flame due to both compression and accelerated motion. The second frame reveals a relatively sharp flame image that resembles (but is a distorted simile of) the flame envelope in the frame immediately preceding shock arrival. The flame has been displaced in the direction of shock propagation and its trailing surface (if visible) is cupped as though the rate of motion were higher both at the top and near the surface rather than higher at the top only as in the Mixed Company films. However, the overall rate appears more rapid than would be expected if the flame were merely responding to compression and flow behind the shock. The explanation for this apparent anomoly may be that the normal yellow-orange flame is undergoing a change of state--for reasons we do not fully understand--into a blue, faintly visible flame at a rate exceeding bulk flow. To illustrate magnitudes, in Test 16 the 1.7-psi peak overpressure would be expected to be followed by a fluid velocity no greater than 90 ft/sec. Figure 7 gives frame-by-frame observations of the flame motion and compares this to a straight line whose slope corresponds to 90 ft/sec. Clearly, the yellow-to-blue interface is progressing at a much higher rate. Initially, the trailing edge of the blue flame appears to move at a rate approximating 90 ft/sec and then slows down, indicating that it may be undergoing bulk flow displacement.

## Effect of Barriers

In the test using the 1.75-in. barrier at the forward edge of the fuel bed to interfere with shock-induced flow over the fuel-bed surface (Test 6), the air blast nearly failed to extinguish the flames in spite of the long duration of positive pressure and flow. The motion pictures reveal that the flames were not swept cleanly from the surface and survived the initial pressure pulse to reestablish themselves briefly.

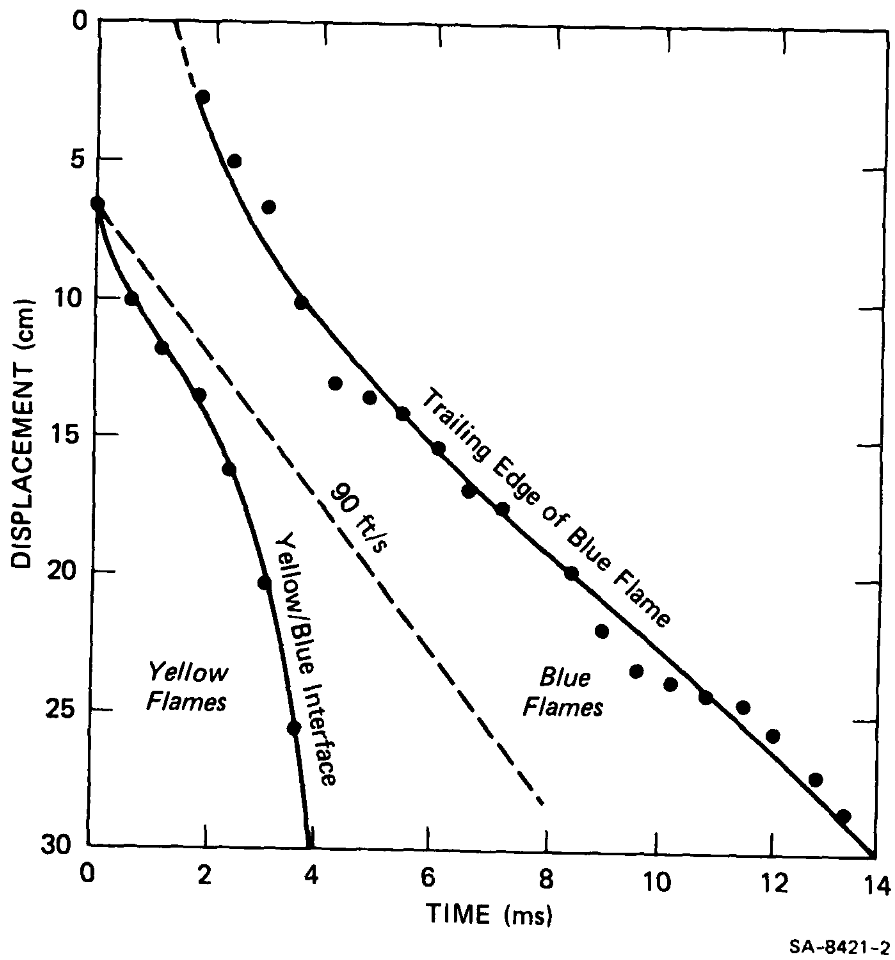


FIGURE 7 ILLUSTRATION OF FLAME MOTION FOLLOWING SHOCK DIFFRACTION, 1.7 psi PEAK OVERPRESSURE

However, a second, even stronger pressure pulse, between about 170 ms and 400 ms following shock arrival, did succeed where the first failed. The waxing-and-waning character of the flames roughly coincides with the pressure time record. Initially, the flames are swept from view except for a blue residual near the surface, behind the barrier. During the following period of about 100 ms, the flames partially recover, filling a substantial volume above the bed with flames that are mixed orange with blue. Then they are again swept away, this time irretrievably, disappearing entirely by 300 ms, close to the time of maximum overpressure in the test section. Clearly, the extinction would not have occurred without the unexpected second pulse, and it is very likely that even with the second pulse, the flames would have survived over a 3-foot-long bed. This is a distinctly different situation from Test 5, where the 1-in. barrier at a point 11 inches upstream of the leading edge of the fuel bed had no stabilizing effect on the hexane-fueled flames; the flames were immediately swept off a 3-foot bed at a rate that matched (or even exceeded) the previous test (Test 4) in which no barrier was present at all. In Test 5 there were flames visible after the shock only in the seven frames immediately following. This corresponds to about 4 ms. Since the camera view includes about a foot (28.7 cm) of bed length, this corresponds to a displacement rate of 250 ft/sec (7175 cm/sec). This is consistent with free-stream particle velocities behind an 8-psi shock.

## CONCLUSIONS AND RECOMMENDATIONS

The limited data resulting from this study, as yet unstructured by a theoretical model, allow us to offer only tentative conclusions. Within limitations of the test facility and conditions imposed, the following conclusions seem justified for the flat-plate geometry, zero angle of attack attitude, and for volatile class-B fuels stabilized mechanically by inert substrates:

(1) Flame displacement is a mechanism of extinguishment.

(2) Extinction threshold conditions scale with fuel bed length; more specifically, for 70 to 300 ms pressure-pulse durations, the critical bed length is approximately proportional to peak overpressure (in the range of 1 to 5 or more psi) and appears proportional to particle displacement during the positive phase. The critical length is, however, only about 1/6 of the particle displacement for the waveform used.

(3) Results do not seem to depend on the texture of the substrate.

(4) The effect of a barrier is pronounced and apparently very sensitive to location. Even a small perturbation introduced into the flow immediately in front of the fire may allow it to survive air blast conditions that would otherwise readily blow the fire out. However, this "stabilizing wake" does not persist to appreciable downstream distances (less than, say, ten barrier heights).

The single datum on a class-A fuel is totally inadequate to permit comparisons with class-B fuels. However, the displacement mechanism seems to apply also to extinction of flames over class-A fuels in flat-plate configurations oriented edge-on to the incident shock.

This experimental work should be continued. In particular, data on class-A fuels in practical configurations are needed. Acquisition of such data may be delayed, however, until a suitable thermal radiation source can be provided for use with the shocktube. We urgently recommend the development of such a source.

In the meantime, the imbedded heater technique that was developed in a preliminary way in the work reported here should be improved and used to ignite class-A fuels. Also, more work should be done on effects of barriers and other flow perturbing factors to better define the stabilizing influences of complex targets.

At the same time, a separate theoretical development should proceed with continual interaction between theoretician and experimenter. An effort should be made to minimize the work required to test the seemingly endless variety of variables and their combinations that pertain to practical situations of concern. This might be done by deriving data-correlating parameters from an engineering (i.e., similarity-principle) analysis based on the heat and mass transport process coupled to the relevant processes of chemical change (i.e., pyrolysis and combustion). This development also should be supported by a more fundamental experimental study of the physics of interaction of air blast with fire processes in somewhat more idealized fuel bodies than we are using in the present study. Such fundamental studies can, nevertheless, be conducted in the same shocktube facility.

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## Appendix A

## ESTIMATION OF FLUID DISPLACEMENT

Following passage of the shock, having peak overpressure $p_o$ and propagation velocity U, the free-stream fluid flows past some fixed reference point at a velocity u(t). This velocity is assumed to be a monotonically decreasing function of time from an initial value $u_o$ at t = o to rest at $t_+$, the end of the positive pressure phase. Further, it is assumed that $u_o$ is uniquely determined by $p_o$, and, in the range of overpressures used in this study,* that

$$u(t)/p(t) = 50 \left(\frac{ft/s}{psi}\right) .$$

During this period of down-tube flow, a fluid "particle" displaces a distance

$$d_+ = \int_o^{t_+} u(t)dt$$

$$= 50 \int_o^{t_+} p(t)dt \text{ (in feet)} .$$

Accordingly, an estimate of fluid displacement can be computed from an integration of the pressure-time record.

Figure A-1 is a plot of $d_+$, computed as above, versus $p_o$ for those cases in which we have made graphical integrations of the pressure-time records. The data clearly fall into two sets, corresponding to the longest and shortest durations available with the present facility. Data from the short-duration set are well approximated by the empiric:

$$d_+/p_o = 4.2(ft/psi)$$

This result was used to construct the air displacement scale in Figure 6.

*See "The Effects of Nuclear Weapons," Third Edition, S. Glasstone and P.J. Dolan (eds.), U.S. Government Printing Office, p 97 (1977).

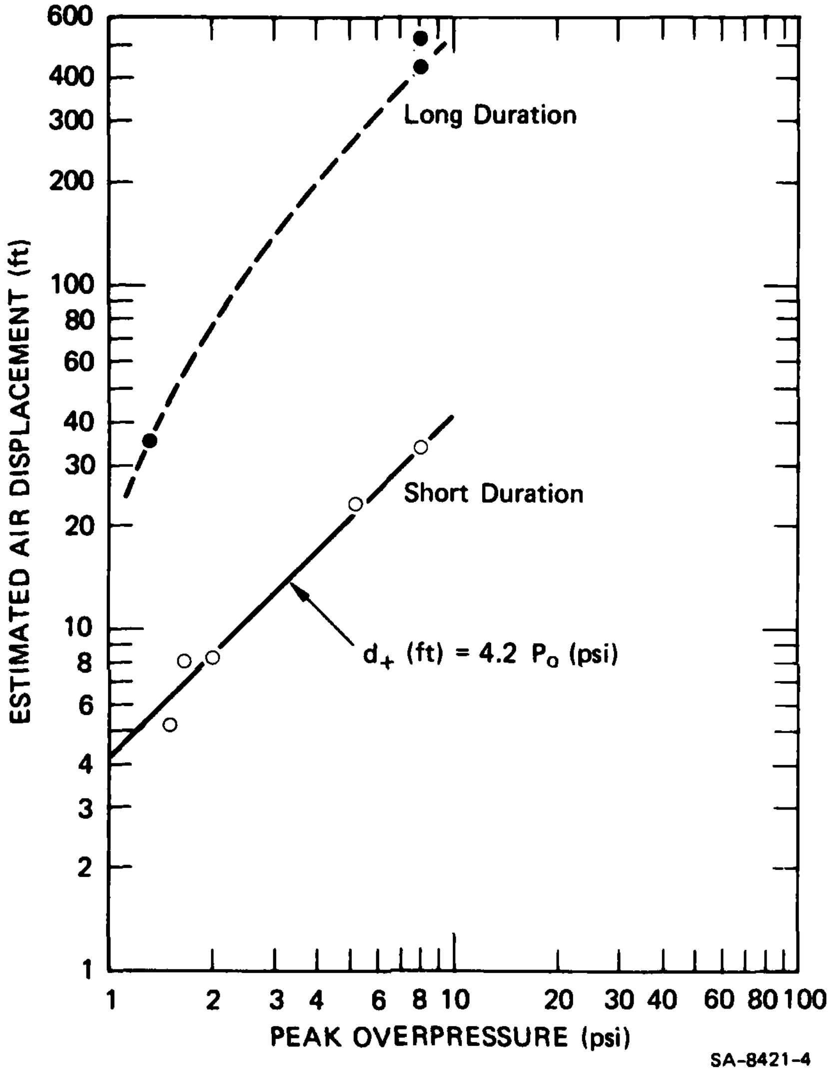


FIGURE A-1 EMPIRICAL RELATIONS BETWEEN DISPLACEMENT AND OVERPRESSURE

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EXPERIMENTS ON EXTINCTION OF FIRES BY AIR BLAST: by Stanley B. Martin. SRI Project PYU 8421, pages plus append., Contract No. DCPA01-79-C-0245, FEMA Work Unit No. 2564A, Unclassified (January 1980).

Current uncertainties regarding interaction of blast waves on fires preclude reliable estimates of the outcome of a nuclear attack on the United States. This study focuses on the threshold air-blast condition for extinguishing fires initiated by thermal radiation. Flame blowout tests with simulated nuclear air-blast waves were conducted in the SRI-developed shocktube facility on class-B fires both in a flat plane geometry and stabilized behind barriers. The results support the concept of flame displacement as a mechanism of extinguishment. Data on class-A fuels in practical configuration are needed next.

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# EXPERIMENTS ON EXTINCTION OF FIRES BY AIRBLAST

**Flame Displacement as an Extinction Mechanism**

DETACHABLE SUMMARY

January 1980

Annual Report

By: Stanley B. Martin

Prepared for:

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## DETACHABLE SUMMARY

### Problem and Objective

The combined blast and fire effects of nuclear explosions in urban areas have been recognized and documented as operationally significant and important to strategic planning. These effects include (1) the dynamic influences of the air shock passing over ignited materials (i.e., fire enhancement or extinguishment) and (2) perturbations in fire growth and spread caused by the blast-induced disarray in the target.

Current uncertainties regarding the various interactions of blast waves and their effects on fires (and on the potential for fire spread to increase damage, destruction, and life loss) are major obstacles to defense planning and countermeasure preparation; they can even affect National Security decision-making at the highest levels. Concisely stated, these uncertainties substantially preclude any reliable quantitative estimates of the outcome of nuclear attack on the United States and of our capacity to survive and recover from such an attack.

Several of the critical uncertainties are:

(1) Threshold air-blast conditions for the extinction of fires initiated by thermal radiation.

(2) Process of rekindle in fuels perturbed by blast.

(3) Effects of structural damage on the processes of fire growth and spread.

(4) Descriptions of debris fields in sufficient detail to permit calculation of fire-spread rates and burning rates.

The Work Unit reported here is an experimental investigation of the first area of uncertainty listed above. The overall objective of this project is to determine and evaluate the physical variables that govern extinction of sustained burning, in representative urban fuels, caused by exposure to simulations of airblast from nuclear explosions. This is a report of

the first year's results, summarizing a somewhat preliminary effort limited to flat-plate geometry in edge-on attitude to the incident shock.

## Experimental Method

Flame blowout tests were run in the SRI-developed shocktube facility, which is specifically designed for investigating the interactions of blast with fire by direct observation of the phenomena and dependence of these phenomena on the basic characteristics of nuclear air-blast waves. The facility provides repeatability of test conditions and convenience of operation, and allows many tests to be conducted in a relatively short experimental program at reasonable cost. Systematic investigation is possible through independent variability of air-blast characteristics over the practical range of values for civil defense concerns.

This facility has been used during 1979 for experiments in air-blast blowout, mostly of Class-B (i.e., hexane-fueled) fires. Only a modest experimental effort was possible because modification of the facility to accommodate these experiments absorbed a substantial part of the available funds.

## Findings

The limited data resulting from this study, as yet unstructured by a theoretical model, allow us to offer only tentative conclusions. Within limitations of the test facility and conditions imposed, the following conclusions seem justified for the flat-plate geometry, zero angle of attack attitude, and for volatile class-B fuels stabilized mechanically by inert substrates:

(1) Flame displacement is a mechanism of extinguishment.

(2) Extinction threshold conditions scale with fuel bed length; more specifically, for 70 to 300 ms pressure-pulse durations, the critical bed length is approximately proportional to peak overpressure (in the range of 1 to 5 or more psi) and appears proportional to particle displacement during the positive phase. The critical length is, however, only about 1/6 of the particle displacement for the waveform used.

(3) Results do not seem to depend upon the texture of the substrate.

(4) The effect of a barrier is pronounced and apparently very sensitive to location. Even a small perturbation introduced into the flow immediately in front of the fire may allow it to survive air-blast conditions that would otherwise readily blow the fire out. However, this "stabilizing wake" does not persist to appreciable downstream distances (less than, say, ten barrier heights).

The single datum on a class-A fuel is totally inadequate to permit comparisons with class-B fuels. However, the displacement mechanism seems to apply also to extinction of flames over class-A fuels in flat-plate configurations oriented edge-on to the incident shock.

## Recommendations for Further Work

This experimental work should be continued. In particular, data on class-A fuels in practical configurations are needed. Acquisition of such data may be delayed, however, until a suitable thermal radiation source can be provided for use with the shocktube. We urgently recommend the development of such a source.

In the meantime, the imbedded heater technique that was developed in a preliminary way in the work reported here should be improved and used to ignite class-A fuels. Also, more work should be done on effects of barriers and other flow perturbing factors to better define the stabilizing influences of complex targets.

At the same time, a separate theoretical development should proceed, with continual interaction between theoretician and experimenter. An effort should be made to minimize the work required to test the seemingly endless variety of variables and their combinations that pertain to practical situations of concern. This might be done by deriving data-correlating parameters from an engineering (i.e., similarity-principle) analysis based on the heat and mass transport process coupled to the relevant processes of chemical change (i.e., pyrolysis and combustion). However, this development should be supported by a more fundamental experimental study

of the physics of interaction of air blast with fire processes in somewhat more idealized fuel bodies than we are using in the present study. Such fundamental studies can, nevertheless, be conducted in the same shock-tube facility.